

**AFRL-IF-RS-TR-1998-140**

**Final Technical Report**

**July 1998**



**ASYNCHRONOUS, DISTRIBUTED, SCALABLE  
ALGORITHMS FOR INTELLIGENT REASONING  
WITH GEOGRAPHICALLY DISPERSED, HYBRID  
KNOWLEDGE BASES**

**University of Maryland**

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**DARPA Order No. 5D30**

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**19980911 018**

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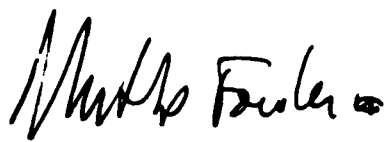
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AFRL-IF-RS-TR-1998-140 has been reviewed and is approved for publication.

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**ASYNCHRONOUS, DISTRIBUTED, SCALABLE ALGORITHMS FOR  
INTELLIGENT REASONING WITH GEOGRAPHICALLY DISPERSED,  
HYBRID KNOWLEDGE BASES**

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Contractor: University of Maryland  
Contract Number: F30602-93-C-0241  
Effective Date of Contract: 15 September 1993  
Contract Expiration Date: 14 September 1997  
Short Title of Work: Asynchronous Distributed, Scalable,  
Algorithms for Intelligent Reasoning with Geographically Dispersed,  
Hybrid Knowledge Bases

Period of Work Covered: Sep 93 - Sep 97

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Approved for public release; distribution unlimited.

This research was supported by the Defense Advanced Research  
Projects Agency of the Department of Defense and was monitored by  
Joseph Carozzoni, AFRL/IFTB, 525 Brooks Road, Rome, NY  
13441-4505.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE July 1998		3. REPORT TYPE AND DATES COVERED Final, Sep 93 - Sep 97
4. TITLE AND SUBTITLE ASYNCHRONOUS, DISTRIBUTED, SCALABLE ALGORITHMS FOR INTELLIGENT REASONING WITH GEOGRAPHICALLY DISPERSED, HYBRID KNOWLEDGE BASES			5. FUNDING NUMBERS C - F30602-93-C-0241 PE - 62301E PR - A716 TA - 00 WU - 01	
6. AUTHOR(S)  V. S. Subrahmanian				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  University of Maryland Office of Research Administration and Advancement College Park MD 20742			8. PERFORMING ORGANIZATION REPORT NUMBER  N/A	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  Defense Advanced Research Projects Agency      Air Force Research Laboratory/IFTB 3701 North Fairfax Drive                              525 Brooks Road Arlington VA 22203-1714                              Rome NY 13441-4505			10. SPONSORING/MONITORING AGENCY REPORT NUMBER  AFRL-IF-RS-TR-1998-140	
11. SUPPLEMENTARY NOTES  Air Force Research Laboratory Project Engineer: Joseph A. Carozzoni/IFTB/(315) 330-7796				
12a. DISTRIBUTION AVAILABILITY STATEMENT  Approved for public release; distribution unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Integrating data and knowledge from multiple heterogeneous sources, each one possibly with a different underlying data model, is not only an important aspect of automated reasoning, but also of retrieval systems where queries can span such multiple sources. These sources can be as different as relational or deductive databases, object bases, constrained data (e.g. knowledge bases), structured files (e.g. spreadsheets), or even arbitrary program packages encapsulating specific knowledge, often in a hard-wired form accessible only through function calls. Many queries can only be answered if data and knowledge from these different sources are available. In 1991-92, Gio Wiederhold proposed the pioneering concept of a mediator - a program that integrates multiple databases. The principal goal of this project was to develop a platform for the creation of mediated applications. Such a platform would provide a mechanism within which mediators may be developed for a variety of applications. The platform itself would be application independent, and would provide a variety of underlying technology and services that would be critical to the success of any specific application involving the use of mediation technology. The product of this research is a system called WebHERMES (Heterogeneous Reasoning and Mediation System).				
14. SUBJECT TERMS  Software, Knowledge-Based Systems, Intelligent Database			15. NUMBER OF PAGES  36	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT  UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE  UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT  UNCLASSIFIED	20. LIMITATION OF ABSTRACT  UL	

# 1 Project Goals

Integrating data and knowledge from multiple heterogeneous sources, each one possibly with a different underlying data model, is not only an important aspect of automated reasoning, but also of retrieval systems where queries can span multiple such sources. These sources can be as different as relational or deductive databases, object bases, (constraint) knowledge bases, or even (structured) files and arbitrary program packages encapsulating specific knowledge, often in a hard-wired form accessible only through function calls. Many queries can only be answered if data and knowledge from these different sources are available.

In 1991–92, Gio Wiederhold proposed the pioneering concept of a *mediator* – a program that integrates multiple databases. However, while the goals of precisely what objectives a mediator would satisfy were clear, how these objectives would be accomplished and implemented was not clear. *The principal goal of this project was to develop a platform for the creation of mediated application. Such a platform would provide a mechanism within which mediators may be developed for a variety of application. The platform itself would be application independent, but would provide a variety of underlying technology and services that would be critical to the success of any specific application involving the use of mediation technology.*

In this project, we have developed a formal, theoretically solid framework for the creation and deployment of mediators that access distributed data sources, and shown that this mathematically justified framework scales up to large scale applications involving integrated access not only to multiple databases, but also to multiple

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data structures, and software packages located at diverse networked sources. The resulting system, called WebHERMES, is accessible to any user who has access to the world-wide web through any standard Web browser. This includes access from Unix workstations, PCs, MACs, as well as palmtop computing devices such as the Philips Velo or the US Robotics Pilot.

The organization of this report is as follows. Section II explains the main scientific contributions of this project. Section III explains the software that has been developed. Section IV specifies what Educational Objectives have been accomplished from this project. Section V presents a list of all publications acknowledging this contract.

## 2 Awards/Recognition

The HERMES project, and its participants, have received significant recognition for their work on this project, from a variety of external sources. These are listed below:

- **National Young Investigator Award**, 1993 to V.S. Subrahmanian (PI), National Science Foundation.
- **Maryland Distinguished Young Scientist Award**, V.S. Subrahmanian (PI), Maryland Science Center and the Maryland Academy of Sciences, 1997.
- **Association for Computing Machinery (ACM) Washing Chapter Samuel Alexander Award**, 1997, Kasim S. Candan (graduate research assistant funded by this contract), for an outstanding doctoral dissertation.
- **Business Week Magazine** highlights the accomplishments of Sibel Adali who received her PhD for her work on this project.
- **Publications**: Over 30 publications in top-quality, archival scientific journals, and 16 papers in leading scientific conferences were published due, in part, to support received under this contract.

## 3 Scientific Accomplishments of Project

The HERMES (Heterogeneous Reasoning and Mediator System) project was started in Sep. 1993. During this time, we have developed:

- A language in which mediators can be expressed
- A compiler within which mediators expressed in the above language can be implemented
- A distributed computation framework so that the mediator compiler can access data at multiple sites across the network

- A set of techniques to optimize queries to such distributed heterogeneous repositories
- A set of techniques to incrementally create materialized mediated views (better known as data warehouses) consisting of information from multiple sources
- A set of techniques to specify security policies in mediated systems, as well as process updates in secure mediators
- Web client access to mediated applications
- A unified framework for representing and manipulating multimedia data located across the Internet.

We will now describe briefly, our contributions in each of these areas.

### 3.1 Mediator Language

We have proposed the following concepts for the HERMES mediator language. A domain,  $D$ , is an abstraction of databases and software packages and consists of three components: (1) a set,  $S$ , whose elements may be thought of as the data-objects that are being manipulated by the package in question, (2) a set  $F$  of functions on  $S$  – these functions take objects in  $S$  as input, and return, as output, objects from their range (which needs to be specified). The functions in  $F$  may be thought of as the predefined functions that have been implemented in the software package being considered, (3) a set of relations on the data-objects in  $S$  – intuitively, these relations may be thought of as the predefined relations in the domain,

In our system, called HERMES (“Heterogeneous Reasoning and Mediator System”), a domain call is a syntactic expression of the form

$$\text{domainname} : \text{domainfunction}(\langle \text{argument1}, \dots, \text{argumentn} \rangle)$$

where  $\text{domainfunction}$  is the name of the function, and  $\text{argument1}, \dots, \text{argumentn}$  are arguments to that function. Intuitively, a domain call may be read as: in the domain called  $\text{domainname}$ , execute the function called  $\text{domainfunction}$  on the arguments

$$\langle \text{argument1}, \dots, \text{argumentn} \rangle .$$

The result of executing this domain call is coerced into a set of entities that have the same type as the output type of the function  $\text{domainfunction}$  on the arguments

$$\langle \text{argument1}, \dots, \text{argumentn} \rangle .$$

A domain-call atom (DCA-atom) is of the form

$$\text{in}(X, \text{domainname} : \text{domainfunction}(\langle \text{arg1}, \dots, \text{argn} \rangle))$$

polymorphic set membership predicate. For example,

$$\text{in}(A, \text{paradox} : \text{select}_{\epsilon} q('phonebook', "name", "josmith"))$$

is a DCA-atom that is true just in case  $A$  is a tuple in the result of executing a selection operation (finding tuples where the NAME field is JO SMITH on a relation called PHONEBOOK maintained in a PARADOX database system.

A mediator is a set of rules of the form

$$A \leftarrow D1 \& \dots \& Dm | A1 \& \dots \& An$$

where  $A1, \dots, An$  are atoms, and  $D1, \dots, Dm$  are DCA-atoms.

We have studied the syntax and semantics of this language exhaustively, yielding a clean amalgamation of multiple databases, data structures and software packages. We have developed algorithms that are provably correct that answer queries to these databases very efficiently.

## 4 Mediator Compiler

We have built a mediator compiler within which queries to HERMES mediators may be expressed and processed. There are two important aspects to constructing a mediator: domain integration and semantic integration. Intuitively, domain integration is the physical linking of the data sources and reasoning systems, while semantic integration is the coherent extraction and combination of the information provided by the data and reasoning sources, serving a given purpose.

The HERMES compiler takes as input, a mediator expressed in the HERMES language expressed in the preceding section, and produces as output, a set of data structures that may be used to process and execute queries in the Hermes query language. When a user of an application mediator built in HERMES expresses a query, the mediator rules defined with the application mediator expands the query into a set of subqueries. Such subqueries may be subqueries either to the HERMES system itself, or to external data sources accessed by the HERMES mediator. Here is an example of how a HERMES query is processed.

**Example Query:** Let  $rte1$  be a ternary predicate such that  $rte1(O, D, R)$  is satisfied iff  $R$  is a route from the origin to an unspecified destination such that the destination has an airfield as well as certain types of ammunition. For this, we may define the following clause in the mediator:

```
rte1(O,D,R) ←
    in(P1,paradox: select=(facilities, facility, "airfield")) &
    in(P2,dbase: select=(supplies.item, "ammunition")) &
    = (P1.place, P2.place) &
    in(D, spatial: findpt(P1.place)) &
    in(R, rp: route(O,D)).
```

To obtain the result from a given location  $\ell$ , we can pose the query

$$\leftarrow rte1(\ell, D, R).$$



This is then processed as follows: PARADOX is invoked which SELECTs all tuples from the `facilities` relation that have the an airfield facility. P1 is then instantiated to one of the selected tuples. Next DBASE is then queried to SELECT all tuples from the `supplies` relation that have the `item` field set to `ammunition`. P2 is instantiated to one such tuple. A check is made to see that P1 and P2 have the same `place` field. In other words, this ensures that *single* place is found with both ammunition and an airfield? If not, the HERMES inference engine looks for other possible instantiations of P1 and P2 that satisfy these constraints. Finally, the xy-location of the place P1.place is computed using the spatial domain, instantiating D, and RP is called to find a route from the origin  $\ell$  to D.

The HERMES query processing algorithm is a sound and complete algorithm for processing queries to heterogeneous mediated systems.

## 5 Query Optimization and Caching

An important issue that we have studied is ways to make the processing of queries in heterogeneous reasoning systems more efficient. We advocate the intelligent use of high-speed caches to avoid computations whenever possible. To accomplish this we introduce the concept of an “invariant”, i.e. an expression about the known input/output relationships of a program that can be processed by the mediator. We have shown how such caches may be maintained, and how the query processing procedure can make better use of these caches, given the knowledge about different packages, to reduce the complexity of query execution. Our methods are sound and complete.

It is possible that in the processing of the rules in the mediator, “similar” function calls to external programs will need to be executed several times since the same kind of information may be requested over and over by different users. Backtracking is another reason for such a situation. Calling an external program is usually a costly operation because of the memory, CPU requirements and possible network delays. Furthermore, actual packages may levy charges for accessing them. Suppose there is a way to guess “some” of the answers that will be returned by an external call. If a refutation is found by substituting one of these answers, then there is no need to execute the external domain call. This is accomplished by caching the answers returned by previous external calls and re-using them when needed. Similarly, if there is a way of knowing that a function is not defined for some inputs, whenever it is called for these inputs, we can terminate the search down a path of the search space.

The challenge of this approach lies in deciding which sets of answers are relevant, and in representing the input/output behavior of some external functions. This information is stored in the system with the help of some explicit rules which will be referred to as “invariants”. Invariants are expressions specifying the relation between the set of answers returned by an external call, its arguments and other possible external calls.

As an example, consider the following invariant :

$$T2 \geq T1 \Rightarrow f(T2) \supseteq f(T1)$$

The above expression can be read as follows: if  $T2 \geq T1$ , then all the solutions of  $f(T1)$  are also solutions of  $f(T2)$ . Hence, if the set of answers for  $f(T1)$  were previously stored in a cache, then these answers can be re-used whenever the function  $f(T2)$  is called; if none of the answers to  $f(T1)$  satisfies the rest of the query then  $f(T2)$  needs to be computed. An example of such an invariant is given below:

**Example 1** Suppose `relation` is a constant in the mediator which refers to a relational database with the usual selection operators. For example, `select≤(R,F,V)` selects all the tuples in table `R` such that the value of the field `F` is less than or equal to `V`. Then, the following are possible invariants for different `select` functions.

$$\begin{aligned} T2 \leq T1 &\Rightarrow \text{relation:select}_{\leq}(R, \text{Field}, T1) \supseteq \\ &\quad \text{relation:select}_{\leq}(R, \text{Field}, T2). \\ T2 \geq T1 &\Rightarrow \text{relation:select}_{\geq}(R, \text{Field}, T2) \supseteq \\ &\quad \text{relation:select}_{\geq}(R, \text{Field}, T1). \end{aligned}$$

The first invariant can be read as: For any given database `R` and field `Field` in the domain `relation`, whenever  $T2 \geq T1$  is satisfied, all the tuples that are in `relation:select≥(R,Field,T2)`, are also in `relation:select≥(R,Field,T1)`.

**Example 2** Suppose the domain `spatial` is a spatial data structure such as a point quadtree storing points in two-dimensional space. The function `vertical_slice(File,X,Dist)` in this domain returns all the points that have `X`-coordinates between `X+Dist` and `X-Dist`, in other words all the points that are in the vertical slice taken from `X-Dist` to `X+Dist`. The following is an invariant about this function:

$$\begin{aligned} \text{Dist1} \leq \text{Dist2} &\Rightarrow \\ &\quad \text{spatial:vertical\_slice}(\text{File}, X, \text{Dist2}) \supseteq \\ &\quad \text{spatial:vertical\_slice}(\text{File}, X, \text{Dist1}). \end{aligned}$$

which states that whenever the `X`-coordinate is fixed, the points in a vertical slice are contained in any of the bigger vertical slices. We can easily write similar invariants for other spatial functions. The invariant for the `horizontal_slice` function is the same as `vertical_slice`. As for the `range(X,Y,Dist)` function which returns all the points that are at distance `Dist` from point `(X,Y)` (i.e. all points `(X1,Y1)` such that  $(X - X1)^2 + (Y - Y1)^2 \leq \text{Dist}^2$  we can write the following invariants:

$$\begin{aligned} \text{Dist1} \leq \text{Dist2} &\Rightarrow \\ &\quad \text{spatial:range}(\text{File}, X, Y, \text{Dist2}) \supseteq \\ &\quad \text{spatial:range}(\text{File}, X, Y, \text{Dist1}). \\ |X1 - X2| \leq |\text{Dist1} - \text{Dist2}| &\Rightarrow \\ &\quad \text{spatial:range}(\text{File}, X2, Y, \text{Dist2}) \supseteq \\ &\quad \text{spatial:range}(\text{File}, X1, Y, \text{Dist1}). \end{aligned}$$

Our research proposes a cost-based optimization technique that caches statistics of actual calls to the sources and consequently estimates the cost of the possible execution plans based on the statistics cache. We investigate issues pertaining to the design of the statistics cache and experimentally analyze various tradeoffs. We also present a query result caching mechanism that allows us to effectively use results of prior queries when the source is not readily available. We employ the novel *invariants* mechanism, which shows how semantic information about data sources may be used to discover cached query results of interest.

## 6 Maintaining Mediated Views/Warehouses

A *mediated materialized view* (often called a data warehouse) is a view of a body of distributed heterogeneous data that is precomputed and stored as a cache of the sort described in the preceding section. As in the case of traditional views, mediated views are materialized for efficiency reasons. A materialized view can be affected by two kinds of updates, namely updates to the materialized view, and updates to the underlying sources.

If an update of the first kind occurs to a view, whether materialized or not, the problem of reflecting the update correctly by changing the base tables appropriately needs to be addressed. This problem is called the *view update problem* and has been discussed extensively for relational, deductive, and object-oriented databases. However, our objective is slightly different. We do not necessarily assume that an update occurring to a view has to be reflected within some underlying source. Instead, we assume that the view itself — or, to be more precise, its definition — is affected by the update. This kind of update affecting the view's definition is typically not treated within the view update literature. One exception are deductive databases, where the addition or deletion of rules to the definition of an intensional predicate is discussed by Teniente. However, they neither materialize nor preprocess the view for efficiency reasons.

Within the traditional context, the second case occurs if an update to a base table occurs which possibly affects a materialized view. The resulting problem — preserving the consistency of the view — is called *view maintenance*. However, since we do not necessarily materialize the view upon the underlying sources of our mediated views but instead perform materialization by unfolding the view definition as independent as possible from the underlying sources, the traditional view maintenance problem occurs quite differently to us. Hence, the traditional view maintenance problem and our problem do not intersect but complement each other.

Subsequently, we treat both kinds of updates to materialized mediated views and show how they can be handled efficiently. More specifically, the primary aim is to specify how to efficiently maintain views of mediated systems such as those that may be constructed in HERMES when insertion and deletion requests of both of the above two kinds are made. As in the standard case, a *materialized view* in mediated systems may be thought of as a set of facts that can be concluded from the mediator rules.

However, we show that more generally, a materialized mediated view may be regarded as a set of *constraint* atoms that are not necessarily ground. Taking materialized views to be sets of constrained atoms leads to a number of advantages:

1. First of all, it allows us to perform updates to *constrained databases* as well as mediated systems. To our knowledge, there are currently no methods to incrementally maintain views in constrained databases.
2. We show for updates of the second kind that even in the case of unconstrained databases, such as those considered by Gupta, Mumick and Subrahmanian, (which we have been told is now used by AT& T for billing purposes) this approach leads to a simpler and more efficient deletion algorithm than the deletion algorithm, DRed presented in earlier.

In other words, not only have we developed efficient algorithms for view management, these algorithms also (in some cases) improve upon existing algorithms for view management in traditional relational databases.

## 7 Ontology Management

Any mediator, in integrating heterogeneous sources, has to resolve both syntactic and semantic conflicts between (the data in) in the disparate sources. While considerable work has been done on this problem in the context of multi-database systems, little algorithmic support has been developed for resolving (especially semantic) conflicts, and currently, resolving them is largely a responsibility of the mediator developer. We develop appropriate concepts and algorithms for solving the following problems.

- Resolving the conflicts between data coming from heterogeneous sources
- Allowing users to personalize queries so as to address their own needs (e.g., a user from India might want prices returned in Indian Rupees).
- Answering personalized queries.
- Maintaining a mediator against changes to the data sources, in the form of restructuring. Such restructuring may be motivated by the requirements of the local user community of the source. Our ideas and techniques apply to any mediator framework, such as the TSIMMIS project at Stanford University, the HERMES project at University of Maryland, the SchemaLog project at Concordia University, the Disco project at Inria, and several others.

## 8 Security in Mediated Systems

Over the last few years, there has been considerable work on security in databases. Most of this work has been limited to the realm of relational databases though of late,

some work has been done on extending these security paradigms to object-oriented databases deductive databases, and other paradigms. Castano et. al. provide a comprehensive description of related work. Despite the differences in the underlying data paradigm, all these frameworks share a single trait that we (cynically?) term the principle of paranoia.

**THE PRINCIPLE OF PARANOIA.** The DBMS must take all steps necessary in order to insure that the user  $u$  cannot to infer any item in a pre-designated set  $\mathcal{S}(u)$  of items that are to be kept secret from the user.

However, with the evolution of the information superhighway, there is now an immense amount of information available in a very wide variety of databases. Wiederhold has proposed the concept of a *mediator* – intuitively, a mediator is a program that integrates multiple databases. Consider a mediator program  $M$  that integrates some software packages  $P_1, \dots, P_k$ . Each of the packages  $P_1, \dots, P_k$  may enforce its own unique *local* security policy. Some may represent completely “open-source” software/data, while others may place certain restrictions on the use of certain facilities and/or data residing within it. In contrast to the principle of paranoia commonly enforced in ordinary databases, mediated systems must attempt to be *maximally cooperative* to the user, yet at the same time, they must respect the security constraints of the individual databases/packages participating in the mediated system. Thus, for instance, two packages  $P_1$  and  $P_2$  may both be able to satisfy a user’s request – however, package  $P_1$  uses secure data, while package  $P_2$  uses open-source data. In this case, the mediated system may reasonably use package  $P_2$  to respond to the user’s query, even though package  $P_1$  feels this data should be kept hidden from the user. Notice that in this case, the user could directly query  $P_2$  and get the data without using the mediator at all, so the mediator might as well do it for him, unless a *global* security condition maintained by the mediator prevents this. Thus, in the case of mediated systems, we may wish to implement a policy of *cautious cooperation*.

**THE PRINCIPLE OF CAUTIOUS COOPERATION.** If a user’s query can be answered using open-source information, then the mediator will answer the query unless doing so will *directly* violate the system’s *global* security constraints. However, the system will always respect the rights of individual packages participating in the mediated system, and ensure that no single package violates its own local security policy.

The principle of cautious cooperation ensures that a given query will cause no direct violation of global integrity constraints, but may leave the path open for future violations or for inferential violations. A slightly more conservative policy, that we term the principle of *conservative cautious cooperation*, will answer a query posed by the user iff the answer to that query will not yield an “inference path” (sequence of open-source queries coupled with logical reasoning) that the user may use to violate security (unless such a path existed prior to the query being issued by the user).

**THE PRINCIPLE OF CONSERVATIVE CAUTIOUS COOPERATION.** If a user's query can be answered using open-source information, then the mediator will answer the query unless doing so will cause there to be a sequence of queries (that only reflect open-source accesses) such that if the user asks this sequence of queries, then he will be able to violate the system's *global* security constraints. However, the system will always respect the rights of individual packages participating in the mediated system, and ensure that no single package violates its own local security policy.

In our research, we have developed techniques by which mediators may be efficiently and scalably extended to encode the principles of paranoia and the principle of cautious cooperation, as well as the principle of conservative cautious cooperation.

## 9 Web Access to Mediator Technology

We have developed algorithms which will take as input, a HERMES mediator  $M$ , and generate as output, an HTML-form that can be used to query mediator  $M$  by any user who has access to the World Wide Web through standard Web browsers such as Netscape and Microsoft Explorer. In particular, as a consequence of this Web-page generation module, users with Web browsers on:

- Unix workstations (e.g. SUNs and DEC's)
- PC devices (e.g. IBM-PC compatibles)
- Wireless/cellular palmtop devices (e.g. The Philips Velo, US Robotics Pilot)

can now access WebHERMES from such devices.

## 10 Heterogeneous Multimedia Databases

Though numerous multimedia systems exist in the commercial market today, relatively little work has been done on developing the mathematical foundations of multimedia technology. We attempt to take some initial steps towards the development of a theoretical basis for multimedia information system. To do so, we develop the notion of a structured multimedia database system. We begin by defining a mathematical model of a media-instance. A media-instance may be thought of as "glue" residing on top of a specific physical media-representation (such as video, audio, documents, etc.) Using this "glue", it is possible to define a general purpose logical query language to query multimedia data. This glue consists of a set of "states" (e.g. video frames, audio tracks, etc.) and "features", together with relationships between states and/or features. A structured multimedia database system imposes a certain mathematical structure on the set of features/states. Using this notion of a structure, we are able to define indexing structures for processing queries, methods to relax queries when answers do not exist to those queries, as well as sound, complete and terminating

procedures to answer such queries (and their relaxations, when appropriate). We show how a media-presentation can be generated by processing a sequence of queries, and furthermore we show when these queries are extended to include *constraints*, then these queries can not only generate presentations, but also generate temporal synchronization properties and spatial layout properties for such presentations. We describe the architecture of a prototype multimedia database system based on these principles.

## 11 An Application to Terrain Reasoning

*The work described here was done jointly with researchers at the US Army Topographic and Engineering Center in Ft. Belvoir, VA.*

In this section, we will describe an application of our work to intelligent terrain reasoning that involves integrating terrain map data, relational data, and planning packages (developed at the US Army Corps of Engineers). The purpose of such an integrated system is many-fold. It can be used as a basis for vehicular navigation in disaster relief situations (e.g. floods, earthquakes, volcanic disasters, etc.), as well as in military mission planning applications. In these applications, a user, who may either be a human or may be an autonomous vehicle, may be interested in posing queries of the following types:

- **(Unknown Destination)** Given a location, find a place that has an airfield as well as certain types of ammunition. Presumably these resources are needed in order for the autonomous/manned vehicle to satisfy its mission.
- **(Route Properties)** Furthermore, no point in the route may be less than 4 miles from an enemy outpost. In this example, in addition to the fact that the destination is unknown, we have the fact that the query asks not only for a route to this unknown destination point, but it asks for a *route that satisfies certain desiderata*, i.e. which satisfies certain conditions that require accessing external databases (e.g. to figure out where enemy outposts lie).

A route planner (which we will call RP) has been implemented at the US Army Topographic and Engineering Center. Given two points, this route planner will find an optimal, least-cost path between these two points (if one exists). Thus, for instance, the query

`rp : route((35,70),(200,98))`

returns the set of least-cost paths from the origin point, (35,70) to the destination point (200,98) that are found by the Army's route planner.

We illustrate how this example may be solved within the HERMES framework, using RP as a domain. For this, let us suppose that we have a relational (PARADOX) database containing a relation called **facilities** having the schema (Name, Facility). Thus, this relation may contain a tuple of the form (*awasa, airport*) denoting that the place, Awasa, has an airport. Other tuples in the relation **facilities** may be similarly interpreted. Suppose there is another (DBASE) database containing a relation

called **supplies** having the schema (Place.Item) - an example tuple in this relation is (*awasa, gas*) specifying that gas is available at Awasa<sup>2</sup>.

#### Example Query:

```
rte2(O.D.R) ← rte1(O.D.R) & good(R).
good(nil) ←
good(cons(H.T)) ← goodpoint(H) & good(T).
goodpoint(H) ← is({}, spatial: range(H.4)).
```

Note the use of the special HERMES predicate `rte1` has been described earlier.

## 12 Software Developed

Appendix A contains a complete user manual of the HERMES software.

## 13 Educational Accomplishments

During the pursuit of this research, we have accomplished the following milestones:

- V.S. Subrahmanian (PI) received the NSF National Young Investigator Award.
- V.S. Subrahmanian (PI) received the Maryland Distinguished Young Scientist Award (Maryland Academy of Sciences).
- 2 PhD's were granted:
  - Sibel Adali received her PhD in 1996 and is currently an Assistant Professor of Computer Science at Rensselaer Polytechnic Institute in Troy, NY.
  - Kasim S. Candan received his PhD in 1997 and is currently an Assistant Professor of Computer Science at Arizona State University in Tempe, AZ.
- Kasim S. Candan (student supported by this contract), received the 1997 ACM Samuel Alexander Award for an outstanding dissertation.
- Sibel Adali's work supporting this contract received Press Highlights in *Business Week Magazine*, June 23, 1997.
- The following students supported in part by this contract received Master's degrees: Charlie Ward, Vadim kagan.

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<sup>2</sup>In practice, these relations will contain much more detail, but we keep them simple here in order to facilitate presentation.



## 14 Publications

The following papers were supported in part by this contract.

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